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REMARKS

The claims in the application remain 28-56.

Favorable reconsideration of the application is respectfully requested.

Claims 28-56 have been rejected under 35 U.S.C. §103 as obvious over U.S. Pat. No. 5,467,184 to Tenjimbayashi. However, it is respectfully submitted the invention recited in all claims pending herein defines patentable subject matter over this reference for the following reasons (reference will be made to preferred embodiments of the present invention illustrated in the drawings of the present application).

The claimed invention explicitly improves reliable evaluation and recording of deformation in an object 1 such as a tire, even in the case of relatively large deformations. As noted in the background portion of the present application, previously recording and analyzing large defects during deformation had been difficult because intervals between various interference lines had been small or negligible, hampering evaluation. The advantageous improvement is explicitly attained by a process and apparatus for recording deformation of the object 1 such as a tire in which a sequence of images of the object 1 is recorded during deformation, phase images are determined from the recorded images using a phase-shifting technique, a differential is formed between two sequential phase images (n+1, n+2), and these differentials are added together, e.g., to the first image. The incremental deformations are thus added together, i.e., integrated, yielding the total deformation of the object 1.

One of the important advantages of the presently claimed invention involves

analyzing deformation of objects automatically <u>and</u> quantitatively, thereby facilitating reliable evaluation and reducing inspection time. As described at page 2, lines 1-5 of the present application, this is attained by the phase-shifting technique where the phase of the radiation from the object 1 is determined by intensity signals from sensor elements 2.

The features of the presently claimed inventive recording method and apparatus together with the accompanying advantages attained thereby are neither taught nor suggested by Tenjimbayashi for the following reasons.

Attention is respectfully called to the enclosed Declaration under 37 C.F.R. §1.132 executed by one of the joint inventors, Rainer Huber. The improvements set forth <u>supra</u> provided by the present invention are described in paragraph 3-5 of Mr. Huber's Declaration. In paragraph 7 of his Declaration, Mr. Huber points out Tenjimbayashi <u>only</u> teaches use of <u>speckle</u> image and do <u>not</u> disclose any <u>phase-shifting</u> technique and generating <u>phase</u> images. Attention is then called in paragraph 8 of the Declaration to the attached excerpt (pages 73-77) from "Digital Shearography" by Wolfgang Steinchen and Lianxiang Yang, SPIE PRESS (2003). As pointed out in paragraph 9 of Mr. Huber's Declaration, Tenjimbayashi merely shows a method of deformation measurement using <u>speckle</u> interferometry comprising the steps of forming a series of <u>speckle</u> images (Figs. 8a-8e) at specified time intervals and using the difference between an appropriate two of the plurality of <u>speckle</u> images to measure the deformation of the object during the time interval between the formation times of the two speckle images (column 1, lines 49-60 and column 5, line 57 - column 6, line 12).

It is then pointed out by Mr. Huber in paragraph 9 of his Declaration quantitative (i.e., numerical analysis) of a deformation without a phase-shifting technique of Tenjimbayashi can be only be accomplished manually by visualization and not automatically by image processing, calling attention to page 73, lines 8-10 of Steinchen et al. Mr. Huber notes in paragraph 9 of his Declaration column 1, lines 49-64 of Tenjimbayashi (cited by the Examiner in paragraph 4 of the Office Action) fails to disclose or suggest any phase-shifting technique and generating phase-images. Accordingly, Mr. Huber concludes in paragraph 9 of his Declaration Tenjimbayashi just teaches the use of speckle images.

At the top of page 3 of the Office Action, the following statement appears regarding Tenjimbayashi:

> ....Tenjimbayashi's method, however, relies on speckle images rather than the phase images as claimed.
>
> Tenjimbayashi's speckle images, however, serve the same function as the phase images in the current application....

However, such conclusion still fails to suggest to Mr. Huber, one skilled in the art, determining phase images from the recorded image, forming a differential between two sequential phase images, and then adding these differentials together as recited in independent Claims 28 and 50 (paragraph 10 of the enclosed Declaration).

Mr. Huber further concludes in paragraph 11 of his Declaration since the analysis of deformation using Tenjimbayashi's speckle images can only be done manually

and qualitatively while the phase-shift technique in the present application can be done automatically and quantitatively, thereby reducing the inspection time and facilitating reliable evaluation, Tenjimbayashi's speckle images, therefore, do not serve an equivalent function as the phase images in the current application.

Accordingly, in view of the forgoing remarks and enclosed Declaration executed by Rainer Huber, it is respectfully submitted all claims pending herein are in condition for allowance. Please contact the undersigned attorney should there be any questions.

Early favorable action is earnestly solicited.

Respectfully submitted,

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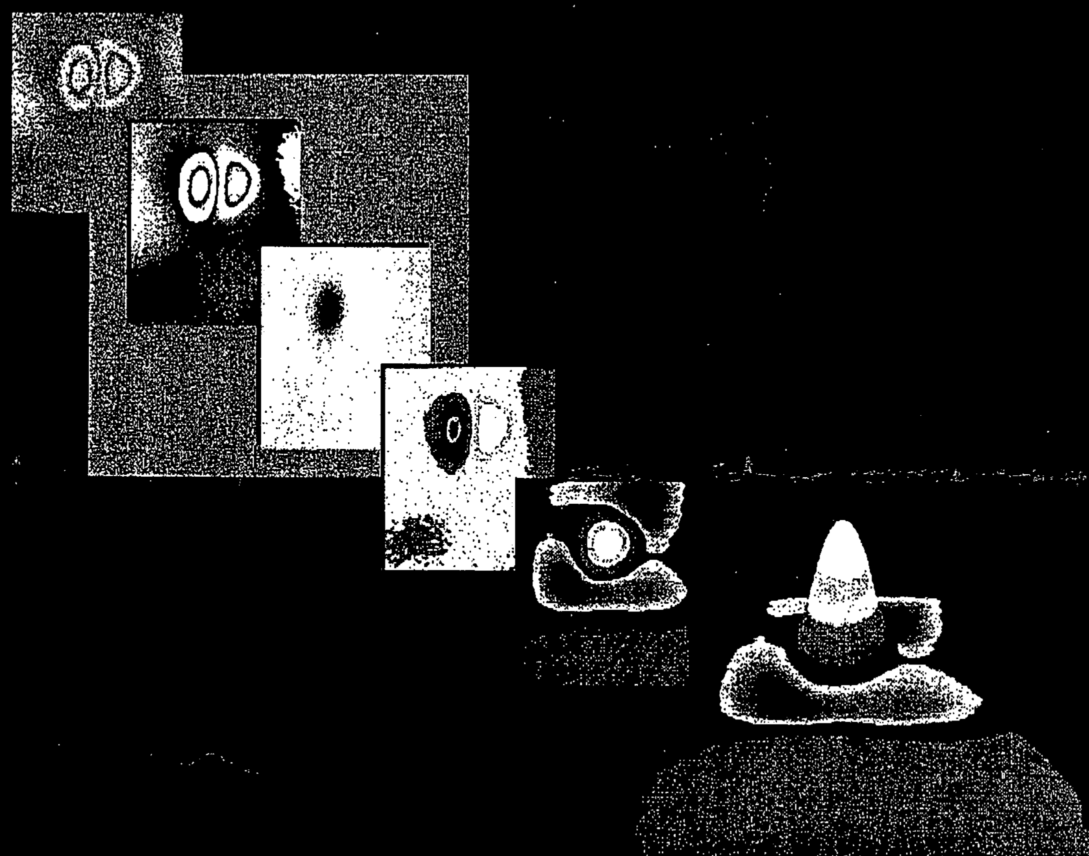
Digital Shearography

Theory and Application of Digital Speckle Pattern Shearing Interferometry



Wolfgang Steinchen
Lianxiang Yang

Digital Shearography

Theory and Application of Digital Speckle Pattern Shearing Interferometry

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Chapter 4

Phase-Shifting Shearography

Development from photographic to simple digital shearography in recent years has launched a technical revolution that makes wet processing and optical reconstruction unnecessary, so that real-time observation of shearogram becomes possible. However, the interpretation of shearogram in simple digital shearography is in the same state as photographic shearography. As with a photographic shearogram, an electronic shearogram cannot be evaluated automatically. Therefore, both methods are candidates for only qualitative investigations. Quantitative (i.e., numerical) analysis of a shearogram without a phase-shifting technique, which is explained in this chapter, can only be done manually by visualization and not automatically by image processing.

Numerical evaluation of a shearogram requires the determination of its relative phase difference Δ. To determine the relative phase change Δ, distributions of the phase differences ϕ and ϕ' have to be calculated first, because $\Delta = \phi' - \phi$. The distribution of the phase difference ϕ can be either the unloaded state or first loading, i.e., preloading, of the object. The distribution of the phase relation ϕ' corresponds to the loaded state, i.e., the second state of deformation. For simplicity, the distribution of the phase difference of a speckle interferogram (or specklegram), ϕ or ϕ', will be described as phase distribution in the following discussion. By applying the phase-shifting technique to simple digital shearography, the shearogram can be observed in real time and evaluated quantitatively as well. This development opens up new prospects in the field of NDT, strain measurement, and vibration analysis.

Time-dependent phase shifting cannot be used for measuring transient processes in components and structures, but it is suitable for static and quasi-static investigations as well as harmonically excited components. Under the above-mentioned circumstances, time-dependent phase shifting is developed further for digital shearography. The time-dependent phase-shifting technique will be referred to in the following description as the phase-shifting technique for short.

4.1 Fundamentals of the phase-shifting technique

Different methods can be applied for determining the phase distribution of an interferogram numerically and automatically. These methods can be divided generally into two categories, i.e., time-dependent and spatial phase-shifting

techniques [1]. The time-dependent phase-shifting method is the most powerful technique for determining the phase distribution of an interferogram. With this method, three, four, or five interferograms of a deformation state are stored sequentially in order to obtain a solvable system of equations consisting of at least three unknowns, i.e., the mean value of the intensity I_0, the modulation of the interference term γ, and the random phase angle or phase distribution ϕ [cf. Eqs. (2.4.4) and (2.4.5)] [2-4]. By applying the spatial phase-shifting technique, the phase distribution can be determined from only a single interferogram [5-7]. It can therefore be applied to vibration analysis, especially for measuring transient processes with a double-pulse laser. The determination of the phase distribution by this technique is not as accurate as the time-dependent method [8, 9], however.

The phase-shifting technique is a method that determines the phase distribution of an interferogram from the measured intensities. As described in Section 2.4, the intensity of an interferogram can be expressed by Eqs. (2.4.4) or (2.4.5). The fact is that the CCD camera can register only the intensity of an interferogram and there are three unknowns (I_0, γ, ϕ) in the intensity equation. To determine the phase distribution ϕ of the interferogram, a system of at least three equations is required. Therefore, a known additional phase φ (usually 120° for each of the three equations) is introduced by shifting the interfering light waves one against the other. Shifting the additional phase φ three times and measuring the intensity I_i results in three equations:

$$\begin{aligned} I_1 &= 2\,I_0[1+\gamma\cos\phi], \\ I_2 &= 2I_0\ [1+\gamma\cos(\phi+120°)], \\ I_3 &= 2I_0\ [1+\gamma\cos(\phi-120°)]. \end{aligned} \tag{4.1.1}$$

The phase distribution of the interferogram can be calculated from the measured intensities as follows:

$$\phi = \arctan\frac{\sqrt{3}\,(I_3-I_2)}{2I_1-I_2-I_3}. \tag{4.1.2}$$

The conditional equation system consists of three, four, or five equations for determining the phase distribution ϕ and ϕ'.

Shifting the additional phase φ five times and measuring the intensity I, five equations are the result:

$$
\begin{aligned}
I_1 &= 2I_0[1+\gamma\cos(\phi-180°)], \\
I_2 &= 2I_0[1+\gamma\cos(\phi-90°)], \\
I_3 &= 2I_0[1+\gamma\cos\phi], \\
I_4 &= 2I_0[1+\gamma\cos(\phi+90°)], \\
I_5 &= 2I_0[1+\gamma\cos(\phi+180°)].
\end{aligned} \tag{4.1.3}
$$

The phase distribution of the interferogram can be evaluated from the determined intensities as follows:

$$\phi=\arctan\frac{2(I_2-I_4)}{-I_1+2I_3-I_5}. \tag{4.1.4}$$

The algorithm is described in the literature [10] and thus it will not be explained further. The conditional equation system consisting of four equations is explained in detail later.

This technique, which has been applied to TV holography and has its origin in earlier publications [2,11], uses three or four measured intensities that are stored digitally and treated so that the TV hologram can be evaluated numerically and automatically. For numerical and automatic evaluation of a shearogram, phase-shifting shearography will be developed further on the basis of simple digital shearography. In the following section the procedure for this technique will be explained, as well as its function for a few applications.

4.2 Arrangement of phase-shifting shearography

The phase-shifting technique is based on the shifting of a known additional phase in one of two beams which interfere each other. In TV holography the known additional phase is generated by shifting the reference beam against the object beam. Shearography does not use an additional reference beam; therefore the generation of the additional phase is more difficult. By moving the biprism shown in Fig. 2.1-3 in the x-direction, an additional phase is adjusted [12]. But the distance required for the movement is too large, owing to the small wedge angle of the biprism. Although an additional phase can be generated by this method, a lateral movement of the ray is created because of the large shifting of the biprism [13], which reduces the accuracy of the phase calculation.

As a matter of priority, the application of the previously mentioned Michelson interferometer as a shearing device makes the generation of the additional phase very simple. Figure 4.2-1 shows the schematic setup of phase-shifting shearography.

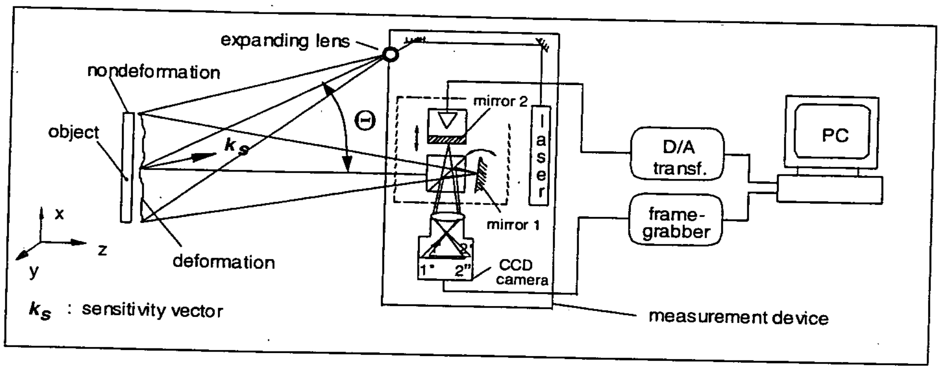

Fig. 4.2-1. The experimental setup of phase-shifting shearography.

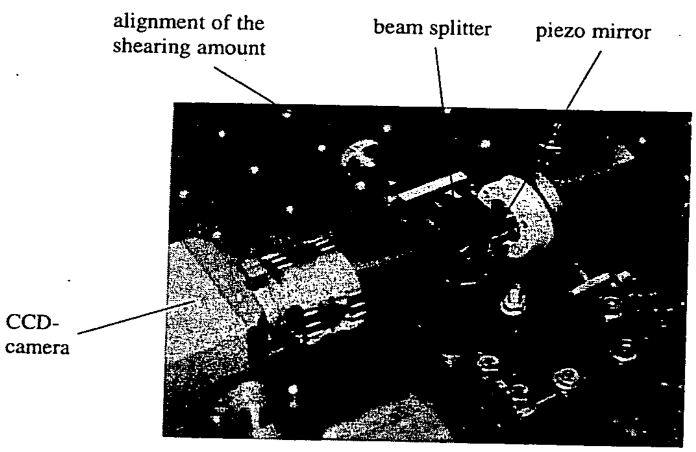

Fig. 4.2-2. CCD camera and Michelson interferometer with a phase-shifting device.

The object to be tested is illuminated by an expanded laser beam. The reflected laser beam passes the Michelson interferometer and is focused on the CCD array of the image plane implemented in the CCD camera. By a small tilting of mirror 1 in the Michelson interferometer, two slightly shifted images of the object are generated. The interferometric superimposition of both speckle interferograms yields a new specklegram in the CCD array. The use of a Michelson interferometer as a shearing device is contrary to one using a wedge or biprism, and it offers the advantage of allowing an adjustment of the magnitude and direction of the shearing by rotating the precision measuring screw belonging to mirror 1 (Fig. 4.2-2).

To generate the required additional phase, mirror 2 of the Michelson interferometer is driven by a piezoelectric crystal (PZT). A linear movement of mirror 2 controlled by the piezoelectric crystal results in the additional phase φ.

When the mirror is shifted for a path δl, the optical path length is changed for 2 δl by the forward and backward path. The additional phase is represented by

$$\varphi = \frac{2\pi}{\lambda} 2\delta l. \tag{4.2.1}$$

To generate an additional phase of $2\pi/3$ (=120°), mirror 2 requires a movement of $\lambda/6$; for an additional phase of $\pi/2$ (=90°), a movement of $\lambda/8$ is required. The control is carried out by a voltage amplifier that moves the mirror according to the voltage feed.

The phase calculation from the three intensities as given in Eq. (4.1.1) requires three movements of the mirror. Recording an interferogram takes approximately 20 ms. The movement of the piezoelectric-driven mirror can be completed within 1 ms. However, the recording of the next interferogram requires a pause of approximately 50 ms to move mirror 2 in order to stabilize the position of the piezoelectric-driven mirror. Storing the three intensities (i.e., three exposures and three movements, including stabilization) requires less than 1 s. But, for the phase calculation from four intensities, four movements of mirror 2 are necessary. In this case, the known additional phase is $\pi/2$ (=90°). The time for storing the four intensities is also less than 1 s.

4.3 Calculation of the relative phase change Δ in a shearogram

Determination of the phase distribution of an interferogram using the phase-shifting method was described in detail in Section 4.1. Theoretically, only three stored intensities for the phase calculation are required owing to the three unknowns. However, phase calculation from four intensities is very simple; thus this method was used to calculate the phase distribution implemented in the Shearwin program (The Shearwin program for data aquisition and evaluation was developed by Lab SHS, University Gesamthochschule Kassel.) The intensity distributions of four frames (images) from four corresponding interferograms can be digitally stored by the hardware component of the frame grabber. Each interferogram is obtained after the phase is shifted for + 90°, i.e., the linear movement of mirror 2 for $\lambda/8$, and it is then stored. The four images result in the following four equations:

$$\begin{aligned} I_1 &= 2I_0[1+\gamma\cos\phi], \\ I_2 &= 2I_0[1+\gamma\cos(\phi+90°)], \\ I_3 &= 2I_0[1+\gamma\cos(\phi+180°)], \\ I_4 &= 2I_0[1+\gamma\cos(\phi+270°)]. \end{aligned} \tag{4.3.1}$$

The magnitude of the phase can be calculated at each point of the speckle interferogram in the undeformed state or for the preload of the object by Eq. (4.3.2) as converted from Eq. (4.3.1):

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